

Strategic Implementation Plan

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Executive Summary

This Strategic Implementation Plan sets forth the NASA Aeronautics Research Mission Directorate (ARMD) vision for aeronautical research aimed at the next 25 years and beyond. It encompasses a broad range of technologies to meet future needs of the aviation community, the Nation, and the world for safe, efficient, flexible, and environmentally sustainable air transportation.

Long-term aeronautics research has long provided the basis for new concepts leading to industry innovation and societal benefits. The future holds new challenges for the aviation system, including continuing growth to meet emerging global demand, integration of unmanned aircraft systems and other innovative vehicle concepts to serve myriad needs, and proactive adaptability to changing conditions – all with minimum adverse impact on the environment. To address these challenges, ARMD will continue its role of undertaking research and development that falls outside the scale, risk, and payback criteria that govern commercial investments.

Analysis of global trends has led ARMD to identify the following three overarching drivers, referred to as Mega-Drivers, which will in large part shape the needs of aeronautical research in the coming years:

- Mega-Driver 1, Global Growth in Demand for High-Speed Mobility: Reflects rapid growth in traditional measures of global demand for mobility.
- Mega-Driver 2, Global Climate Change, Sustainability, and Energy Use: Presents severe challenges in maintaining affordability and sustainability.
- Mega-Driver 3, Technology Convergence: Points to convergence occurring in industry sectors such as materials, manufacturing, energy, and information and communication technologies that will transform aeronautical capabilities.

Six Strategic Thrusts represent ARMD's response to the Mega-Drivers as they affect aviation:

- Strategic Thrust 1: Safe, Efficient Growth in Global Operations
- Strategic Thrust 2: Innovation in Commercial Supersonic Aircraft
- Strategic Thrust 3: Ultra-Efficient Commercial Vehicles
- Strategic Thrust 4: Transition to Low-Carbon Propulsion
- Strategic Thrust 5: Real-Time System-Wide Safety Assurance
- Strategic Thrust 6: Assured Autonomy for Aviation Transformation

Taken together, these Strategic Thrusts constitute a vision for the future of aviation. ARMD's strategic planning addresses research needs associated with these Strategic Thrusts through a hierarchy

of Outcomes, Research Themes, and Technical Challenges. Outcomes defined in terms of three time-frames — near-term (2015 to 2025), mid-term (2025 to 2035), and far-term (>2035) — signify the advances required to address each Strategic Thrust. Research Themes, which support the Outcomes, represent major areas of research necessary to enable the Outcomes consistent with ARMD's roles and capabilities. Each Research Theme includes one or more Technical Challenges, which are funded activities with specific objectives. These Technical Challenges serve as the basis for planning research activities and measuring performance.

ARMD's strategy will continue to focus on high-impact research investments that will enable the transformation of aviation to serve future needs, produce demonstrable benefits, and leverage technology advances outside of, as well as within, traditional aviation disciplines. Major technology foci include alternative fuels and electric or hybrid propulsion, low-sonic-boom supersonic flight, automation and autonomy, and technology convergence to develop transformative solutions, with the ultimate goal of enabling a safe, efficient, adaptive, scalable, and environmentally sustainable global aviation system.

A Letter to the Reader

As you sit down to read this document, you may be enjoying a cup of coffee brewed with coffee beans grown in South America, roasted by your favorite coffee roasting company, and flown to you the next day. Or maybe you are reading this on the screen of a computer with components made in Asia and shipped by air to the manufacturer. The examples are many, but chances are whether you flew today or not, something you needed did. Aviation is an integral part of our economy and impacts our daily lives. Not only does it provide people across the United States and the world a means to travel across oceans and continents, but it is also a primary means of shipping products around the world.

Over the past 100 years, first the National Advisory Committee for Aeronautics, or NACA, and then NASA, directly benefitted our aviation system by performing the cutting edge research and developing the breakthrough technologies that have advanced aircraft design and capability, as well as improved the efficiency and safety of the National Airspace System. Today's aviation system is what it is because of NASA research.

However, as the world becomes more urban in regions such as Asia, more and more people want to travel. Energy prices have driven up the costs of doing business and environmental impacts are of greater concern. As the aviation industry becomes more global, more nations are conducting advanced aeronautics research and developing their own aviation industries. The U.S. aviation industry is now competing in a more dynamic and challenging environment as a result. We in NASA Aeronautics recognize the potential impact of all these trends on our current aviation system and have developed a research strategy to respond.

The NASA Aeronautics Research Mission Directorate Strategic Implementation Plan is the culmination of several years of effort to assess the global trends, analyze how these trends may impact aviation, and determine how we can respond from a research and technology development perspective. In the following pages, you will find details of our planning process, the global trends we identified and the resulting drivers on the aviation industry, the community vision we developed based on input from our stakeholders, and our research role we defined to achieve that vision.

This Strategic Implementation Plan is our first attempt to document our new strategy and vision, and is meant to be a living document through which we communicate with you, our stakeholders, and our research community to elicit feedback. We will be updating this plan as we learn from the research process and as we receive your feedback.

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As such, I ask that you, the reader, accept this document in the spirit in which it was prepared – a living document that serves as the basis of a conversation about how we further develop our community’s vision, and the research strategy that enables transforming our current aviation system to best meet demands and opportunities of the future.

Dr. Jaiwon Shin
Associate Administrator
NASA Aeronautics Research Mission Directorate

Introduction

This Strategic Implementation Plan sets forth the NASA Aeronautics Research Mission Directorate (ARMD) vision for aeronautical research aimed at the next 25 years and beyond. This vision is NASA's synthesis of the aviation community's view of the future of aviation. It encompasses a broad range of technologies, including the contributions of international as well as U.S. organizations that will contribute to these technologies. ARMD will update this document as the technologies mature, new technologies emerge, and the community's needs evolve.

Overview

Aviation is a critically important enterprise for the United States. It integrates the latest knowledge in advanced technologies developed over decades of concerted research. The mission of ARMD is to serve the future needs of aviation by conducting research into, and developing solutions for, the problems of flight. While the specific research problems have changed considerably since NASA's mission was written into the National Aeronautics and Space Act of 1958, aeronautical research remains as important now as it was in the early days of aviation.

The Domestic and Global Roles of Air Transportation

As a primary mechanism for physically connecting countries across the world, air transportation is an integral part of today's U.S. and global economies. Aviation enables U.S. enterprises to operate on a global scale, providing safe high-speed transport of people and goods. It accounts for more than \$1.5 trillion of U.S. economic activity each year and generates a positive trade balance – over \$78 billion in 2014 alone. The aviation industry also supports more than 11.8 million direct and indirect jobs, including more than one million high-quality manufacturing jobs.

Every individual feels the benefits of aviation. Nearly every product created and purchased today has been touched by aviation in some way. Freight valued at more than \$1.6 trillion is moved by air each year. More than 760 million passengers traveled on U.S. airlines in 2014, and air travelers spend more than \$670 billion per year for business and personal travel. In short, the U.S. aviation industry is critical to both economic and societal well-being.

Looking forward, global economic growth and urbanization are driving rapid increases in demand for aviation services, especially in the Asia-Pacific region and other high-growth areas. The International Air Transport Association (IATA) forecasts nearly a billion additional air passengers over the next five years, and demand for new aircraft and equipment is growing to keep pace. This expectation represents a

substantial opportunity for U.S. economic growth and competitiveness, as well as providing a variety of benefits on a global scale.

The Role of Research in the U.S. Aviation Industry

The future promises new roles for the aviation system. For example, just over the horizon lies the potential for unmanned aircraft systems (UAS) to serve myriad needs, from battling wildfires to retail distribution to delivering urgently needed medical supplies at remote locations.

Demand growth and change also pose long-term challenges in efficiency, energy, safety, and environmental effects. New concepts and game-changing technologies will be needed to capture the opportunities of the future. Current technologies and evolutionary improvements will not keep pace with many of these growing challenges, nor will they enable the important and exciting new applications that lead to economic opportunity and societal benefit. For example, growth in demand for air service is forecasted to outstrip the ability to constrain energy use and carbon emissions.

Long-term aeronautics research provides the basis for new concepts that ultimately lead to industry innovation and societal benefit. ARMD focuses on research and technology development that is beyond the current grasp of industry, with emphasis on technologies to achieve societal benefits such as safety assurance and environmental protection. NASA's many partners throughout the aviation community view ARMD as the stewards of the Nation's aeronautics research enterprise.

Much of the research guidance and direction for ARMD's efforts derive from the National Aeronautics Research and Development (R&D) Plan¹ and the NASA Strategic Plan. For example, the 2010 National Aeronautics R&D Plan calls for research supporting mobility, safety, sustainability in energy and the environment, and national security and homeland defense. ARMD has made significant contributions to fundamental understanding in these areas, including technologies that will facilitate implementation of system-wide safety assurance, alternative fuels, vehicle efficiency improvements, and reduction of noise and harmful emissions such as nitrogen oxides (NO_x).

NASA Aeronautics Research Yesterday and Today

The year 2015 marks the 100th anniversary of the founding of NASA's predecessor, the National Advisory Committee for Aeronautics (NACA). Since that seminal event, aeronautics research has expanded from the fundamentals of flight to hypersonic air vehicles, from static performance of airfoils to behavior of complex human-machine systems, and from wood-and-canvas structures to adaptive shape-changing materials.

¹ Executive Office of the President, National Science and Technology Council, "National Aeronautics Research and Development Plan," February 2010

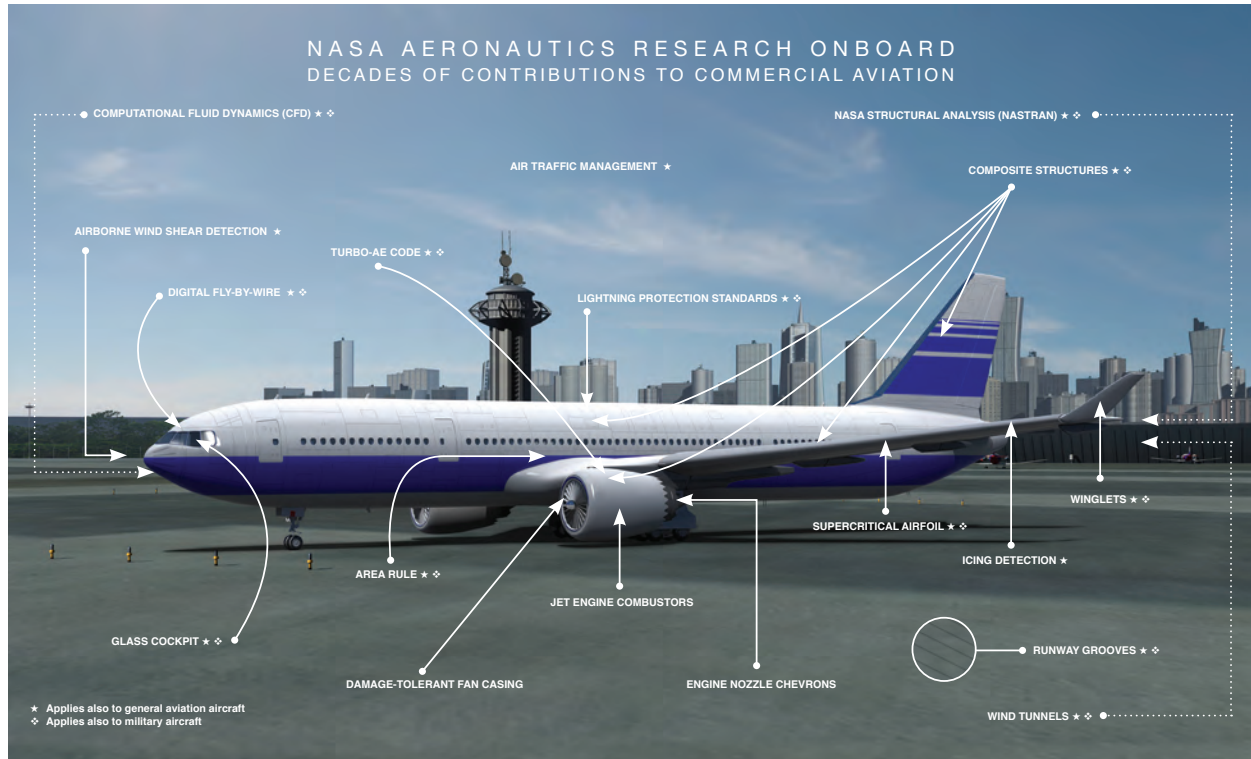


Figure 1. Applications of NASA Research Results in a Modern Commercial Airliner

NASA has a history of undertaking R&D efforts that are outside the scale, risk, and payback criteria that govern commercial investments, with the purpose of proactively transitioning the research findings to the aviation community. NASA aeronautics research has delivered results producing substantial benefits for air transportation in the established ARMD focus areas of fundamental aeronautics, air traffic management, and aviation safety. These results have transformed aviation to the benefit of the national economy, travelers, and shippers, as well as the global environment. As an example, Figure 1 illustrates major features of modern commercial airliners that have been made possible by ARMD research.

The history of NASA research begins with the establishment of the NACA on March 3, 1915, by a rider to the Naval Appropriations Act. The legislation chartered the new organization to “supervise and direct the scientific study of the problems of flight, with a view to their practical solution.” Throughout the last century, research has involved a combination of empirical knowledge gained from ground and flight testing, development of theory and analytic methods, and confirmation by physical demonstration. This research has encompassed an ever-broadening array of technologies, enabling increased performance, enhanced safety, greater efficiency, and reduction of adverse environmental impact.

Initial NACA research focused on the physics of flight, with work involving wind-tunnel tests and flight tests of both models and full-scale aircraft. These tests and the development of theory addressing the aerodynamics of aircraft resulted in greatly increased aircraft speed and range. In the 1930s and 1940s, NACA developed airfoil shapes for wings and propellers that found their way into the designs of many U.S. aircraft of the time, including a number of important World War II-era aircraft such as the P-51 Mustang.

This period also saw the expansion of NACA's research into flying qualities as it began to examine aircraft behavior as a human-machine system. In 1941, a pioneering NACA report, "Requirements for Satisfactory Flying Qualities of an Airplane," by R.R. Gilruth, defined the first set of requirements for the handling characteristics of an aircraft; this work grew into the Cooper-Harper handling-qualities scale for aircraft, which is still in use today.

After World War II, the NACA began to work on the goal of supersonic flight, working closely with the U.S. Air Force and Bell Aircraft to design the first supersonic airplane – the X-1 experimental aircraft. This collaboration marked the NACA's first effort in dealing with the initial design and construction of a research airplane. At the same time, refinement of theory led to further aerodynamic improvements, such as development of the swept-wing concept by Robert T. Jones in 1945 and invention of the area rule concept by Richard Whitcomb in 1951. Development of the axial flow compressor in the 1950s, which became the basis for modern turbojet and turbofan engines, reflected further expansion of the NACA's research horizons.

Following the 1958 Space Act, which established NASA as the successor to the NACA, aeronautics research expanded to address flight beyond Earth's atmosphere. The X-15 research aircraft set an altitude record of 354,000 feet in 1963 and a record speed of Mach 6.7 in 1967. Research topics supporting this and other efforts included compressible flow aerodynamics, high-temperature materials, aircraft structures, and reaction controls. Notable achievements include development of the widely used NASA Structural Analysis (NASTRAN) tools in the 1960s, and initial development and application of computational fluid dynamics (CFD) in the 1970s.

In the 1970s and 1980s, research in supercritical airfoils, winglets, riblets, laminar flow control, and propulsion enabled further advances in performance, embodied in a vigorous flight demonstration program that included the Quiet Short-haul Research Aircraft, XV-15 tiltrotor research aircraft, and X-29 forward-swept-wing flight research aircraft. In this period, the scope of aeronautics research grew to include a number of important safety enhancements such as digital fly-by-wire controls, "glass cockpits," airborne wind-shear detection, microwave landing systems, and head-up displays.

NASA's research contributed significantly to a transformation of commercial air transportation following the introduction of jet airliners beginning in the 1960s. Aircraft cruise speed increased 70% between

1960 and 1990, and energy efficiency doubled in terms of passenger miles per unit of fuel consumed. In the U.S. during the same period accidents per departure dropped by 90% and annual passenger miles flown increased tenfold.

Accomplishments since 1990 demonstrate not only further expansion of ARMD's research, but also a shift to treating aviation as a complex system of systems that integrates a wide variety of technologies to provide safe, efficient, and environmentally sustainable air transportation. These accomplishments include the following, among many others:

- Development of FutureFlight Central full-scale airport operations simulator, simulations of the National Airspace System (NAS), and development of air traffic control and air traffic management tools.
- Exploration of air vehicle and propulsion concepts for energy efficient aircraft, including flight demonstrations of the Blended Wing Body (BWB) X-48B testbed and initiation of research into electric propulsion technology.
- Integration of human factors, guidance, displays, and intelligent flight controls into safety research.
- Further research in aircraft structures, composites, and high-temperature materials.
- Flight demonstration of techniques to shape sonic boom signatures to reduce sonic boom intensity.
- Further development of physics-based and multidisciplinary tools for aircraft design and analysis.

These and other efforts have made significant contributions to further reductions in accident rates worldwide, while U.S. passenger miles continued to grow by more than 50% since 1990, and aircraft became quieter and more energy efficient. Thanks in large measure to technology features attributable to ARMD research, commercial aircraft now entering service are 20% more energy efficient and have a noise footprint 60% smaller than the aircraft they will replace.

This brief historical overview illustrates how ARMD research has produced large benefits by enabling transformative and far-reaching advances in aeronautics. Development of a sound knowledge base and advances in analysis and simulation have enabled the NACA and NASA to expand their aeronautical research perspectives within necessarily constrained resources. The history of NASA aeronautics also points up the continuing need to expand and adjust the scope of ARMD's research to address the public good, meet emerging needs of the aviation community, and exploit new technologies not previously associated with aviation. ARMD's strategy continues to focus on making efficient investments to enable the transformation of aviation to serve future needs, enable demonstrable benefits, and leverage technology advances both within and outside of traditional aviation disciplines.

NASA Aeronautics Vision for the 21st Century



U.S. leadership for a new era of flight

6 Strategic Thrusts



Safe, Efficient Growth
in Global Operations



Innovation in Commercial
Supersonic Aircraft



Ultra-Efficient
Commercial Vehicles



Transition to
Low-Carbon Propulsion



Real-Time System-Wide
Safety Assurance



Assured Autonomy for
Aviation Transformation

NASA Aeronautics Strategy

While past NASA aeronautics research has provided the U.S. aviation industry with transformative technologies, recent global trends call for a shift in focus beyond traditional research areas. In defining NASA's approach to meeting future aviation needs, the 2014 NASA Strategic Plan sets forth a bold objective for aeronautics research in Strategic Objective 2.1: *"Enable a revolutionary transformation for safe and sustainable U.S. and global aviation by advancing aeronautics research."* ARMD is responding with an equally bold vision embodied in this Strategic Implementation Plan.

ARMD's Strategic Planning Process

While ARMD research to date has made many important contributions to air transportation, analysis of global trends indicates that more and different research is needed to keep U.S. aviation safe, robust, and competitive, while also addressing global needs. The Strategic Implementation Plan will guide research across a wide range of technology initiatives, helping to sustain the Nation's aeronautical leadership and supporting U.S. industry's ability to meet the needs of global aviation markets.

ARMD's vision, therefore, addresses the wider roles of aviation and aviation research organizations on a global scale. In evaluating those roles, ARMD recognized that some research needs do not require NASA's expertise, and that other needs that are within ARMD's range of expertise are more properly served by other research organizations. ARMD's research strategy aims to operate productively within that collaborative global research environment, building on current leadership while enabling revolutionary advances.

Figure 2, on page 16, depicts the hierarchy of elements that guides ARMD's aeronautics research planning.



Figure 2. ARMD's Aeronautics Research Planning Framework

The *Mega-Drivers* are three overarching trends that will in large part shape the needs of aeronautical research in the coming years. For each Mega-Driver, ARMD has identified research that is both within the capabilities of ARMD's expertise and resources and beyond the capabilities of industry.

The *Strategic Thrusts* represent ARMD's overarching view of the community's response to the Mega-Drivers as they affect aviation. Taken together, the Strategic Thrusts constitute a vision for the future of aviation.

Outcomes supporting each Strategic Thrust signify the advances required to address the Strategic Thrusts. Because the Outcomes generally involve implementation of ARMD-developed technologies, they must rely on engagement and contributions from the broader aviation community.

Research Themes, which support the Outcomes, are defined as major areas of research necessary to enable the Outcomes consistent with ARMD's roles and capabilities. The Research Themes represent ARMD's long-term vision of pursuing research in particular technology areas. Each Research Theme addresses one or more Technical Challenges, representing funded activities with specific objectives. The Technical Challenges serve as the basis for planning research activities and measuring performance.

Global Trends and Drivers

The three Mega-Drivers that emerged from the trend analysis — growth in air transportation demand; climate change, sustainability, and energy use; and technology convergence — are critical vectors that shape major aeronautics research needs and structure ARMD's response. ARMD has established six Strategic Thrusts on the basis of an analysis of how these global trends will potentially determine the future of aviation.



Mega-Driver 1: Global Growth in Demand for High-Speed Mobility

A century-long trend of migration into cities across the globe is now generating urban growth at a level equivalent to seven Chicago-sized cities per year. At the same time, there has been a trend toward higher speed transport. In 1990, buses, automobiles, and railroads accounted for 91% of the world's traffic volume, leaving only 9% to the high-speed transport modes of air and high-speed rail. But growth in urbanization and wealth by 2050 could increase the demand for high-speed transport to more than 40% of the world's traffic volume.²

For example, the economies of both China and India have been growing more than twice as fast in a 20-year span as did the U.S. economy during its most economically expansive 50-year period (1900-1950). As a result, these countries are expected to account for half of the world's middle class population by 2050.³ The world is also becoming increasingly urban: two thirds of the world's population will live in urban centers by 2050.⁴ Since the urban middle class constitutes a major air transportation market, growth in this population segment will dramatically increase the need for greater, faster, and more efficient air mobility.

IATA projects that the number of air passengers will grow eightfold between now and 2050.⁵ To support that growth in demand, high-technology aircraft, powered by advanced renewable energy sources, will serve intercontinental traffic through a dozen global gateways, connecting at 50 to 75 regional U.S. hubs with air service to local airports.

This expanded and increasingly distributed demand for air travel will require increased high-technology manufacturing capacity. Rising demand will also have to be satisfied with efficient resource use to satisfy cost constraints and limit adverse environmental impacts.

² Transportation in a Climate Constrained World, Andreas Schafer, et al, MIT Press, 2009

³ Karen Ward and Frederic Neumann, Consumer in 2050: The rise of the EM middle class, HSBC Global Research, October 2012

⁴ United Nations Department of Economic and Social Affairs, World Urbanization Prospects: The 2014 Revision

⁵ International Air Transport Association, Vision 2050, February 2011

**Mega-Driver 2: Global Climate Change, Sustainability, and Energy Use**

Fuel is currently a significant driver of the cost of air transportation. According to IATA, fuel is the only major element of air transportation cost that has grown significantly over time. For example, prices of jet fuel rose by about a factor of six between the 1990s and 2012. Fuel made up only 10% of total airline costs in 1995, but it increased to almost 30% by 2011. Despite recent volatility in fuel prices, evidenced by a 20% reduction in the cost of jet fuel since the 2012-2013 peak, energy costs are projected to continue to rise over the long term, affecting affordability of air transportation and sustainability of current models of operation.

In terms of environmental impact, air transportation accounts for about 2% of the world's CO₂ emissions.⁶ While this is a relatively small share, continued growth in air transportation could lead to larger effects. The industry has ambitious goals for reducing generation of CO₂ to enable sustainable growth and address climate change. These goals are to improve system-level fuel efficiency by 1.5% per year through 2020, achieve carbon-neutral growth beyond 2020, and by 2050 to reduce CO₂ emissions to 50% of 2005 levels.⁷ Achieving these goals will require affordable renewable fuels and new low-carbon propulsion system concepts, as well as energy-efficient aircraft and operations.

**Mega-Driver 3: Technology Convergence**

Technology convergence, widely defined as the combination of two or more different technologies in a single device or product, has historically played a major role in technological innovation. This seemingly simple definition, however, masks the fact that systems embodying convergent technologies have often led to radical changes in affected industries and supply chains, marketing and distribution, infrastructure, and uses of the system, along with wide economic and social ramifications.

Evolution of the Internet and its uses provides an obvious, but far from unique, example. Past examples in aviation include convergence of analytical theory with computational capabilities and new materials that have made possible today's air vehicles. Another example is the various technologies that have converged in the Global Positioning System and its applications for navigation and air traffic control. A current example is UAS, which have brought in new producers, users, technologies and missions, and posed new issues related to privacy, regulation, and airspace management. Today, rapid advances in energy, materials, and cyber-physical systems across a broad range of industries represent major examples of technology convergence that promise to transform aviation.

6 Data from United Nations Intergovernmental Panel on Climate Change, quoted by Air Transport Action Group at <http://aviationbenefits.org/environmental-efficiency/aviation-and-climate-change/>, accessed December 11, 2014

7 IATA Resolution on the Implementation of the Aviation "CNG2020" Strategy, June 2013

Biofuels and electric power as sources of energy for air vehicles will converge with technologies for energy storage and vehicle propulsion, as well as new infrastructure for distribution. Additionally, electric power allows efficient use of distributed propulsion, which can change the way aircraft are designed and controlled, leading to new vehicle configurations with enhanced performance, improved energy efficiency, and reduced CO₂ emissions.

New materials, such as composites with tailored strength properties and ceramics for high-temperature applications, will continue to replace customary metal structures and components. With these materials come new producers and new means of manufacture. Convergence with advanced computational methods, robotics, and vehicle design concepts will lead to widespread use of 3-D printing, monolithic structures, shape-changing and multifunctional materials, and other new capabilities to reduce weight, lower manufacturing cost, enhance production flexibility, and improve vehicle performance.

Cyber-physical systems convergence is transforming operational concepts as increasingly intelligent systems enable highly networked systems-of-systems, remote operations, and on-demand systems and services. These advances have promoted innovations such as distributed self-services, exemplified by check-in kiosks at airports, on-demand shared automobiles, and Internet streaming. Machine autonomy and robotics could lead to autonomous on-demand aviation that would radically transform personal mobility and aviation services.

Thus, technology convergence is expected to amplify the benefits of new concepts and technologies in existing as well as emerging aviation markets. However, technology convergence brings new risks and hazards that must be understood and mitigated, such as the creation of new potential safety issues. Technology convergence may also affect the future demand for aviation by enabling innovations such as high-fidelity, multisensory telepresence that could reduce the demand for air travel by partially substituting for physical transportation, although the expanded networks that telepresence enables may also increase aggregate demand for aviation in ways that are hard to predict today.

ARMD seeks to leverage rapid advancements in these technologies and standards across many sectors, as well as emerging operational concepts enabled by the convergence of these technologies, to develop revolutionary solutions for future aviation challenges.

Community Dialogue

In addition to strategic analyses and inputs from subject matter experts and senior stakeholders, ARMD's planning incorporates mechanisms for wide dialogue with the aviation community. To help identify important research areas and challenges of the future, ARMD has frequently engaged the aviation community to understand what its stakeholders believe are priority research areas. Regular discussions have engaged domestic and international partners and experts from industry, academia, and government. Interactions have included regular reviews of ongoing research by federal advisory committees and dialogue sessions with the National Research Council's Aeronautics Research and Technology Roundtable.

These sessions made it evident that the aviation community's highest priorities for research lie in safety, highly efficient aircraft, the evolution of the Next Generation Air Transportation System (NextGen), and UAS access to the NAS. Facilitating advances in these areas will require the development of tools for more innovative virtual testing, and verification and validation of complex systems. Additionally, flight research continues to be a critical element in the maturation of technology, and it can help to establish strong public-private partnerships. Serving these expressed community needs forms an integral part of ARMD's research plans.

Additionally, ARMD recognizes that its research will affect, and be affected by, the work of a wide array of U.S. and international researchers. For that reason, ARMD places major emphasis on maintaining communications and collaborative relationships with the full range of researchers working in government agencies, industry, and academia.

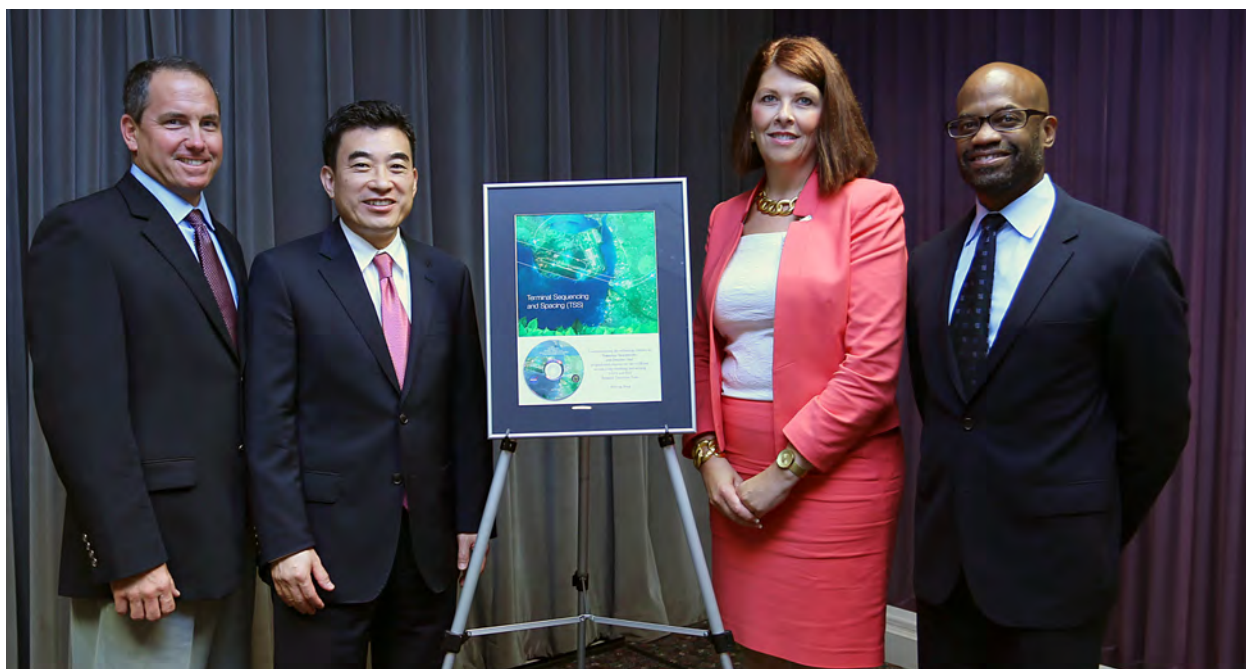
Strategic Partnerships

Partnerships with other government agencies, industry, academia, and foreign aeronautics agencies leverage ARMD's investments through joint efforts that complement NASA's internal capabilities, provide access to a wide range of technologies beyond the traditional aeronautics portfolio, and facilitate technology transfer to more mature states of development and eventual implementation. Integrated technology demonstrations typically include selected industry or government partners who contribute their own funding or knowledge. These partnerships also give ARMD deep insight into the goals and needs of the aviation community, as well as providing user feedback and facilitating industry engagement early in the technology development cycle.

ARMD collaborates closely with the Federal Aviation Administration (FAA) to support that agency's decision making and to improve the performance of the NAS, as well as with the Department of Defense (DoD) and other government agencies to leverage technology investments. Industry partnerships allow rapid insertion of ARMD research results into air vehicles and subsystems, and NAS operations, tools,

and processes. Partnerships with domestic academic institutions support cutting-edge research on emerging aviation technologies and on the education of new researchers in various fields of study. To help address the global nature of air transportation, ARMD also forges partnerships with a wide range of international government entities, such as the International Forum for Aviation Research (IFAR).

To broaden its perspective and impact, ARMD complements its formal partnerships by participating in various public forums including conferences, industry days, working groups, and technical interchange meetings. These activities help to identify needs and areas of potential technical interest that could produce future partnership opportunities.



In 2014, NASA, American Airlines and the Federal Aviation Administration (FAA) marked the official transfer from NASA to the FAA of the Terminal Sequencing and Spacing tools, which helps controllers determine the most fuel-efficient, continuous-descent approach into airports. (l to r) Tim Campbell, American Airlines; Jaiwon Shin, NASA; Teri Bristol, FAA; Ed Bolton, FAA.

Image Credit: Maria C. Werries

Strategic Response

ARMD has formulated six Strategic Thrusts to act as the link between its strategic vision and its research plans. In combination, these Strategic Thrusts respond to the needs of aviation to 2035 and beyond. The Strategic Thrusts are set forth as follows:



Strategic Thrust 1: Safe, Efficient Growth in Global Operations

Within the United States, NextGen is the focus for a modernized air transportation system that will achieve much greater capacity and operational efficiency while maintaining or improving safety and other performance measures. ARMD will contribute specific research and technology to enable the continued development of NextGen and beyond. Projected growth in air travel will require a sustained focus on reducing safety risks to maintain acceptable levels of safety; to that end, ARMD will work with the FAA, the Commercial Aviation Safety Team (CAST), and others to perform research and to contribute technology addressing current and future safety risks. Similar ongoing international developments, such as the European Union's (EU's) Single European Sky Air Traffic Management Research (SESAR) effort, are being globally harmonized through the International Civil Aviation Organization (ICAO).



Strategic Thrust 2: Innovation in Commercial Supersonic Aircraft

Development of efficient, cost-effective, and environmentally sound commercial supersonic transports could not only be a game changer for transcontinental and intercontinental transportation, but could also provide an opportunity to maintain U.S. leadership in aviation systems, and to generate economic and societal benefits in a globally linked world. ARMD will perform selectively focused research and advance groundbreaking technologies to overcome the major environmental and efficiency barriers to market innovation in supersonic transport. Since overcoming these barriers will likely involve modifications to regulations and certification standards for supersonic flight, ARMD will conduct its research in cooperation with the FAA, ICAO, and other aviation regulatory agencies.



Strategic Thrust 3: Ultra-Efficient Commercial Vehicles

Large leaps in aircraft efficiency, coupled with reductions in noise and harmful emissions, are critical to the aviation community's roadmap for achieving greatly improved environmental sustainability. ARMD will develop critical technologies to enable future generations of subsonic fixed wing and vertical lift commercial aircraft that lessen environmental impacts while maintaining safety and improving operating economics. Toward this end, ARMD will coordinate with the DoD on dual-use technologies and concepts, and with the FAA's Continuous Lower Energy, Emissions and Noise (CLEEN) program on high Technology Readiness Level (TRL)⁸ civil demonstrations.

⁸ Technology Readiness Levels are used to identify the maturity of a technology, from TRL 1 through TRL 9. For example, TRL 1 indicates that information from basic scientific research is now taking technology from an idea to a practical application. TRL 9 describes when a technology has been fully incorporated into a larger system. NASA typically continues work through TRL 6, the point at which the technology is transferred to the community for further testing and/or manufacturing and implementation.



Strategic Thrust 4: Transition to Low-Carbon Propulsion

While high levels of aircraft and operational efficiency are required for the future, they will not be enough to produce absolute reductions in carbon emissions. Therefore, ARMD seeks first, to enable the use of alternative fuels, and second, to foster a fundamental shift to innovative aircraft propulsion systems that have the potential to produce very low levels of carbon emissions relative to the energy used. In support of this Strategic Thrust, ARMD will participate in developing and implementing the National Alternative Jet Fuel Strategy sponsored by the Aeronautics Science and Technology Subcommittee of the National Science and Technology Council. ARMD will also coordinate with the DoD and FAA to perform research, and to contribute concepts and technology for alternative propulsive system architectures.



Strategic Thrust 5: Real-Time System-Wide Safety Assurance

Commercial aviation is the safest mode of travel. This accomplishment results from decades of continuous improvement through proactively managing hazards, incidents, and risk of accidents. With technology advances in sensors, networking, data mining, prognostics, and other analytic techniques, the aviation community can now envision a day when it can recognize safety risks as they develop in real time and then implement strategies that prevent those risks from becoming safety issues. ARMD will lead systems research in this area and demonstrate the feasibility of integrated, system-wide safety assurance.



Strategic Thrust 6: Assured Autonomy for Aviation Transformation

Ever-increasing levels of automation and autonomy are transforming aviation, and this trend will continue to accelerate. Safe integration of UAS into the NAS, for example, requires research in multiple areas, including communications, human-machine interfaces, sense-and-avoid, and separation assurance. ARMD will lead in the research and development of new technologies for the safe integration of UAS in the NAS, verification and validation of innovative systems, advanced human-machine harmonization, and highly reliable trusted systems.

Strategic Thrust Convergences

While the Strategic Thrusts define approaches to supporting the community's vision for the future of aviation, they are expected to evolve in response to changes in the Mega-Drivers and the emergence of new global trends. ARMD views these Strategic Thrusts as mutually supportive and, in some cases, converging vectors. For example, as technologies move to more integrated systems, Strategic Thrusts 1 (Growth in Global Operations), 5 (Safety), and 6 (Autonomy) may converge, enabling autonomic system concepts that increase capacity and efficiency while maintaining or enhancing system safety. Such convergence could enable systems that simultaneously achieve capabilities that have previously been considered as conflicting objectives subject to tradeoffs. Adaptive systems are a good example of such concepts. Similarly, convergence of Strategic Thrusts 3 (Ultra-Efficient Vehicles), and 4 (Low-Carbon Propulsion) will allow selection of optimum combinations of technologies to enable environmentally sustainable aviation that will meet future demand.

Outcomes

Outcomes represent overarching aviation goals that are more than NASA alone can do. They are measurable goals for benefits to be achieved through joint efforts across the aviation community. ARMD research is meant to enable each Outcome, but others (FAA, industry, etc.) have key roles in achieving the Outcome and realizing the community's vision. In combination, the Outcomes for all six Strategic Thrusts articulate possibilities that span the interests and contributions of the entire aviation community.

The Outcomes are divided across the future into near-, mid-, and far-term periods in which research results are transitioned from concept to practice:

- Near-term (2015-2025) Outcomes generally leverage partnerships to demonstrate feasibility of potential applications. They enjoy a greater degree of confidence within the aviation community and generally involve focused technology partnerships to enable the Outcomes.
- Mid-term (2025-2035) Outcomes are often in a transitional stage, aimed at a combination of new concepts and applications within the current system. They reflect applications of emerging technologies, initially within the paradigm of the existing aviation system, but often leading to transformative innovations responsive to future needs.
- Far-term (>2035) Outcomes are more exploratory in nature, focusing on concept exploration and technology research. For these outcomes, ARMD takes a greater role in performing and sponsoring concept exploration and fundamental research.

Research Themes and ARMD's Role

Research Themes comprise major areas of research aligned to specific Outcomes. Unlike Outcomes and Strategic Thrusts, which represent aviation community goals that will be achieved through the community's joint efforts, the Research Themes are more focused. They define the roles that ARMD takes in conducting research that ultimately supports the Strategic Thrusts and Outcomes. In some cases, Research Themes reflect technology convergence that ARMD is seeking by combining rapidly advancing technologies from other fields with traditional ARMD strengths to achieve the Outcomes.

The Research Themes are pursued through programs and project organizations within the programs, and progress is reviewed on an annual basis. The research program offices define the Technical Challenges within each Research Theme and delegate them to the project organizations for execution. The project offices continually monitor their portfolios and develop plans that document the relevant Technical Challenges and how they will be addressed, as well as measures of progress and other programmatic information.

Four programs currently comprise ARMD's research activities:

- The Airspace Operations and Safety Program (AOSP) develops and explores fundamental concepts, algorithms, and technologies to safely increase throughput and efficiency of the National Airspace System. The AOSP also provides stewardship of Strategic Thrusts 1, 5 and 6, ensuring that the Research Themes and Technical Challenges are developed and maintained, responsive to this Strategic Implementation Plan, that enable the Outcomes.
- The Advanced Air Vehicles Program (AAVP) conducts cutting-edge research that will generate innovative concepts, technologies, capabilities, and knowledge to enable revolutionary advances for a wide range of air vehicles. The AAVP also provides stewardship of Strategic Thrusts 2, 3 and 4, ensuring that the Research Themes and Technical Challenges are developed and maintained, responsive to this Strategic Implementation Plan, that enable the Outcomes.
- The Integrated Aviation Systems Program (IASP) conducts research on promising concepts and technologies at an integrated system level, with a focus on flight demonstrations. IASP works with AOSP and AAVP to forecast and plan for needed flight demonstrations in support of all Strategic Thrusts.
- The Transformative Aeronautics Concepts Program (TACP) cultivates multidisciplinary, revolutionary concepts to enable aviation transformation and harnesses convergence in aeronautics and other technologies to create new opportunities in aviation. TACP encourages broad thinking about "Big Questions" that leads to potentially transformative concepts and technologies that could enable revolutionary approaches to the intrinsic challenges of the Strategic Thrusts.

The Research Theme section for each Strategic Thrust also identifies any major risks to achieving the community Outcomes that are targeted for mitigation by planned research. In addition, ARMD conducts crosscutting research in fundamental technologies that support multiple Strategic Thrusts and Research Themes. These crosscutting technologies are summarized starting on page 61.

ARMD will continue to explore new Research Themes as research progresses and community needs evolve. Similarly, Technical Challenges will evolve and eventually be replaced as they are achieved, community needs change, technologies advance, or new issues and technologies emerge.

In sum, ARMD's strategic planning process and dialogue with the aviation community have led to the definition of six Strategic Thrusts, supported by a hierarchy of Outcomes, Research Themes, and Technical Challenges. In this context, ARMD will continue its history of collaboration and partnerships with other members of the aviation community to evolve strategies, assess progress, and pursue a robust set of forward-looking research activities.

“The convergence of technologies we are seeing today, including automation, additive manufacturing, multi-functional structures, and an exciting array of other technologies, enables us to envision entirely new concepts in every aspect of the aviation enterprise. We will see a future with ubiquitous UAS, more highly efficient aircraft configurations, and entirely new propulsion systems. I believe we are on the verge of a new era of flight. And NASA has constructed an aeronautics strategy to help bring the benefits of this new era to the United States.”

~ Dr. Jaiwon Shin
Associate Administrator, Aeronautics Research Mission Directorate



FutureFlight Central at NASA's Ames Research Center is one of the simulation facilities used for integrated testing of new tools designed to improve gate-to-gate air traffic flow.



Strategic Thrust 1:

Safe, Efficient Growth in Global Operations

This section describes Strategic Thrust 1, as well as the community's vision based on priorities identified during dialogue and through strategic analysis that led to development of the Thrust, the Outcomes as capabilities that the aviation community can expect from implementing the results of ARMD research, ARMD's role in implementing the research, and the Research Themes developed by ARMD to support the Outcomes and guide the research conducted within the Strategic Thrust.

Community's Vision

NextGen is the Nation's plan for a modernized Air Traffic Management (ATM) system that will achieve much higher levels of operational capacity and efficiency while maintaining or improving safety and other performance measures. Strategic Thrust 1 responds to the NextGen vision and plan and, further into the future, reaches beyond NextGen to fully capture the opportunities enabled by cyber-physical systems research and other emerging technologies. More efficient aircraft operations will reduce energy consumption, complementing Strategic Thrusts 3 and 4 in offering options for environmentally sustainable aviation.

Throughout the time periods from 2015 to 2035 and beyond, Strategic Thrust 1 also responds to specific safety hazards associated with existing or new aircraft, such as near-term needs to reduce loss-of-control accidents of commercial transports and the long-term need to maintain safety of the NAS in the face of greater traffic volume and an increasing variety of vehicle types and missions.

Outcome for 2015-2025: Improved NextGen Operational Performance in Individual Domains, with Some Integration Between Domains (ATM+1). Over the next decade, implementation of NextGen research results will proceed incrementally to improve efficiency in specific operational domains based on prioritized community needs. For example, the Precision Departure Release Capability, recently developed by ARMD and transferred to the FAA, enables precise aircraft departures to ensure that they seamlessly merge into overhead aircraft streams. This tool increases en route capacity, improves reliability of service, and reduces fuel use. Specific prioritized NextGen improvements such as this will overcome major operational hurdles and choke points, delivering increased efficiency and safety, reducing adverse environmental impact, and producing cost savings for airlines and general aviation.

Outcome for 2025-2035: Full NextGen Integrated Terminal, En Route, Surface, and Arrivals/Departures Operations to Realize Trajectory-Based Operations (ATM+2). The 2025–2035 decade will see transformation of the NAS through introduction of the full array of NextGen technologies, including proactive and prognostic safety practices for air traffic management concepts, reliable and capable automation, management of emerging risks, system modeling to improve predictive capabilities, and integration of

currently separated functions and systems. These advances will increase the capacity, safety, efficiency, reliability, and predictability of the NAS, while accommodating an increasing variety of missions and vehicle types, including full integration of UAS operations.

Outcome for >2035: Beyond NextGen Dynamic Fully Autonomous Trajectory Services (ATM+3).

Research exploration today will enable the Nation to look beyond NextGen after 2035 to simultaneously enhance system safety, flexibility, scalability, and resilience. The beyond-NextGen system will enable global traffic growth, support significant changes in the business-network models of airspace users, and accommodate autonomous aircraft operations. Autonomous system-wide adaptation to real-time conditions and events will enable dynamic optimization of system operations, respond quickly to system perturbations, and serve an expanded variety of aircraft and missions.

ARMD's Role

The technical focus of Strategic Thrust 1 is on future aviation system concepts, operations, and technologies. ARMD plays two primary roles within this Strategic Thrust. The first is to develop key safety and automation technologies and safety-management capabilities that enable and extend the benefits of the FAA's plans for NextGen. The second role is to look beyond current FAA plans by researching and developing innovative concepts and technologies to ensure that a long-term research base is in place to support future planning, to enable transformative approaches to future operations, and to safely extend the capabilities and range of uses of the NAS.

ARMD's research for near-term (2015-2025) applications will focus on early improvements in operational efficiency, safety, and environmental performance by exploiting NextGen's state-of-the-art technologies to improve efficiency in each ATM domain. Technology demonstrations will support the maturation and transition of effective ATM tools. Safety-related efforts will include improved aircraft state awareness technologies to reduce loss-of-control accidents.

Research aimed at the mid term (2025-2035) will enhance system efficiency, predictability, and reliability through integration across domains, enhanced predictive capabilities, and proactive prognostic safety methods. Technology development will include advanced methods for safety risk management, system modeling, automation and human-machine integration, and the introduction of trajectory-based operations.

Exploratory research to support the far-term period (>2035) will look beyond current FAA plans, focusing on innovative concepts to transform the NAS into a flexible, scalable, and resilient system that will dynamically adapt to changing conditions, varying user demand, and system perturbations.

ARMD also plans for continued research in engine and airframe icing to enable air vehicles to safely fly into various types of icing environments. This research will include validated computational and experimental icing simulations, as well as complementary on-board icing sensing radar to enable avoidance

of icing conditions and to facilitate safe operation of current and future air vehicle concepts addressed in Strategic Thrust 3.

Research Themes

The Research Themes described in Table 1, below, support the Outcomes associated with Strategic Thrust 1.

Table 1. Outcomes and Research Themes for Strategic Thrust 1

Strategic Thrust 1: Safe, Efficient Growth in Global Operations			
	2015	2025	2035
Outcomes	Improved NextGen Operational Performance in Individual Domains, with Some Integration Between Domains (ATM+1)	Full NextGen Integrated Terminal, En Route, Surface, and Arrivals/ Departures Operations to Realize Trajectory-based Operations (ATM+2)	Beyond NextGen Dynamic Fully Autonomous Trajectory Services (ATM+3)
Research Themes	<p>Advanced Operational Concepts, Technologies, and Automation Research and development of operational efficiency incorporating proactive safety risk management in operational domains</p> <p>Safety Management for Emergent Risks Research and development of prognostic safety risk management solutions and concepts for emergent risks</p> <p>Integrated Modeling, Simulation, and Testing Development, validation, and application of advanced modeling, simulation, and testing capabilities to assess integrated, end-to-end NextGen trajectory based operations functionality, as well as seamless UAS operations and other future aviation system concepts and architectures</p> <p>Airspace Operations Performance Requirements Advanced research to develop performance requirements, functional allocation definitions, and other critical data for integrated, end-to-end NextGen trajectory-based operations functionality, as well as seamless UAS operations and other future aviation system concepts and architectures</p>		

Major Outcome Risks Addressed by Planned Research

Without further research, limitations of high-fidelity modeling and testing capabilities for advanced solutions to capacity, efficiency, and safety issues may impede the development and implementation of solutions, and hence retard growth in global operations.



This concept of an aircraft that could fly at supersonic speeds over land is being used by researchers to continue to test ideas on ways to reduce the level of sonic booms. Its technologies – the propulsion system and the overall shape – are combined to achieve a lower target perceived decibel level.



Strategic Thrust 2: Innovation in Commercial Supersonic Aircraft

This section describes Strategic Thrust 2, as well as the community's vision based on priorities identified during dialogue and through strategic analysis that led to development of the Thrust, the Outcomes as capabilities that the aviation community can expect from implementing the results of ARMD research, ARMD's role in implementing the research, and the Research Themes developed by ARMD to support the Outcomes and guide the research conducted within the Strategic Thrust.

Community's Vision

Development of efficient, cost-effective, and environmentally sound commercial supersonic transportation could be a game changer for transcontinental and intercontinental travel. Such a development would also help to sustain U.S. leadership in aeronautical science and technology. The Outcomes for this Strategic Thrust represent an approach to supersonic research focusing on groundbreaking technologies that show promise of overcoming the environmental and operational barriers to supersonic commercial aircraft.

Environmental barriers include the adverse impacts of sonic boom noise, airport community noise, high-altitude emissions, and high energy consumption. Successful supersonic commercial aircraft must overcome the current prohibition against supersonic overland flight imposed to prevent public annoyance from sonic boom, and they must contend with or avoid operationally inefficient subsonic flight segments required for integration with existing air traffic. Additionally, high fuel consumption and cost due to inefficient airframe aerodynamics and propulsion system performance result in poor operating efficiency and economics. Of all these barriers, sonic boom noise, which creates an unacceptable impact on both the environment and efficient operations, is viewed as the initial critical barrier to be overcome.

Outcome for 2015-2025: Supersonic Overland Certification Standard Based on Acceptable Sonic Boom Noise. Over the next decade, research will focus on overcoming the adverse impact of sonic boom in order to alleviate public concern and environmental impacts. Success in this research will enable the return of civil supersonic service that was abandoned with retirement of the Concorde in 2003, while expanding those services well beyond the Concorde's limited reach in terms of range and efficiency.

Outcome for 2025-2035: Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports. Building on success in 2015-2025, the subsequent decade (2025-2035) will address the additional challenges of landing and takeoff noise, high-altitude emissions, and fuel efficiency, allowing the introduction of affordable, low-boom, low-noise, and low-emission supersonic transportation.

Beyond 2035, successful introduction of supersonic civil air transportation in 2025-2035 will provide the impetus for further research and development that can ultimately enable supersonic air transportation accessible to a broader range of the traveling public, yielding significant benefits for air travelers, the U.S. economy, and global connectivity.

ARMD's Role

The viability of commercial supersonic service depends on permissible supersonic flight over land and the ability to satisfy the same environmental constraints as those imposed on subsonic aircraft. ARMD's initial technical focus, therefore, is on developing scientifically valid tools and survey techniques to develop the necessary database of community response to sonic boom noise. Once the international community has established a sonic boom level acceptable to the public, ARMD research will focus on enabling vehicle designs that achieve the acceptable level, as well as on technologies required to address other environmental and efficiency barriers to development and production of viable supersonic transports.

Since commercial overland supersonic flight is currently prohibited, ARMD's strategy for the near term (2015-2025) is to focus on enabling establishment of a standard for allowable sonic boom. Because international routes comprise a major share of the potential market for supersonic service, ARMD will work with the international standards community to define sonic boom levels that will be acceptable to the public. In parallel, ARMD will develop and validate analysis tools and technologies intended to enable the design and development of supersonic aircraft with low sonic boom.

ARMD research supporting the mid-term (2025-2035) Outcome objectives will transition as success in achieving a regulatory standard and innovation by industry are expected to lead to the introduction of the first new supersonic aircraft. ARMD will continue to conduct research in technologies to meet the desired boom level in larger aircraft, but will also conduct research in areas related to other challenges to successful supersonic transports. Studies will include the development and ground validation of technologies and tools to reduce propulsion emissions and noise affecting the airport community. Additional research will address airframe, propulsion, and structural and aeroelastic efficiency of low-boom supersonic aircraft.

Research objectives beyond 2035 will depend on the evolution of the market and the prospects for technology solutions to increase efficiency, range, and environmental compatibility of supersonic transport aircraft.

Research Themes

The Research Themes described in Table 2, below, support the Outcomes associated with Strategic Thrust 2.

Table 2. Outcomes and Research Themes for Strategic Thrust 2

Strategic Thrust 2: Innovation in Commercial Supersonic Aircraft			
	2015	2025	2035
Outcomes	Supersonic Overland Certification Standard Based on Acceptable Sonic Boom Noise	Introduction of Affordable, Low-boom, Low-noise, and Low-emission Supersonic Transports	<i>(Outcomes beyond 2035 will depend on market needs and technology solutions)</i>
Research Themes	<p>Understanding and Measuring Community Response to Sonic Booms Research, development, and application of validated methodologies for a field study of community response to enable development of overland sonic boom standards</p> <p>Integrated Design Solutions for Revolutionary High-speed Aircraft Research and development of validated analysis tools and technologies that enable the low-sonic-boom design of supersonic aircraft</p> <p>Minimizing the Airport Community Noise Impact of High-speed Aircraft Research and development of validated analysis tools and technologies to enable low-airport-noise propulsion system designs for supersonic aircraft</p> <p>Increasing Cruise Efficiency and Reducing or Eliminating the Impact of High-altitude Emissions Research and development of airframe and engine analysis tools and technologies to maximize the efficiency and minimize the emissions of supersonic aircraft</p>		

Major Outcome Risks Addressed by Planned Research

The critical risk addressed by this Strategic Thrust is to determine if emerging supersonic aircraft technologies will support the elimination of today's prohibition against overland supersonic flight through the reduction of sonic boom to a publicly acceptable level.



Inside the massive National Full-Scale Aerodynamic Complex at NASA's Ames Research Center, an engineer braces himself against the strong winds as he holds a wand emitting a stream of smoke that's used to visualize "in flight" air flow across the tail. The wind-tunnel tests were of an Active Flow Control system installed on the tail that could someday allow airplane builders to design smaller tails, which would reduce weight, drag and fuel use.



Strategic Thrust 3

Ultra-Efficient Commercial Vehicles

This section describes Strategic Thrust 3, as well as the community's vision based on priorities identified during dialogue and through strategic analysis that led to development of the Thrust, the Outcomes as capabilities that the aviation community can expect from implementing the results of ARMD research, ARMD's role in implementing the research, and the Research Themes developed by ARMD to support the Outcomes and guide the research conducted within the Strategic Thrust.

This Strategic Thrust aims primarily at the two generations of air vehicles that will follow those now being developed. The community vision for this Strategic Thrust is based largely on improved environmental performance to address growing public concern about environmental sustainability, as well as enabling increased efficiency and flexibility of future air vehicles to achieve better economics and reduced fuel use. These future vehicles will support worldwide growth in aviation while facilitating public acceptance by virtue of lower noise and diminished impact on local air quality and climate change.

The Outcomes focus on increasing levels of efficiency and environmental compatibility, reflecting community views on what could be achieved, as well as the vehicle capabilities necessary to meet market requirements and civil air transportation needs in the future. Separate Outcomes are defined for subsonic transport and vertical lift vehicles.

Community's Vision

Subsonic Transport

Community performance goals for subsonic transports include specific levels of reduction in energy consumption, emissions of nitrogen oxides (NO_x), and noise, represented as N+1, N+2, and N+3 performance levels. These goals support reductions in carbon emissions expressed in an IATA resolution that calls for a 1.5% average annual fuel efficiency improvement between 2010 and 2020, carbon neutral growth from 2020 onward, and a reduction of 50% in net emissions by 2050 compared to 2005 levels.⁹ The performance goals also support meeting and exceeding projected noise and NO_x standards, such as those recommended by ICAO.¹⁰

9 IATA Resolution on the Implementation of the Aviation "CNG2020" Strategy, June 2013

10 ICAO Working Paper A38-WP/25, Developments in Civil Aviation and the Environment, July 18, 2013

Table 3, which appears on page 42, presents the performance targets for the N+1, N+2, and N+3 subsonic transports.

Figure 3, from the website of the commercial aviation industry Air Transport Action Group (ATAG),¹¹ illustrates the community view of how carbon neutrality will be achieved through a combination of technology innovation, operational improvements, infrastructure efficiencies, and economic measures to incentivize emission reductions.

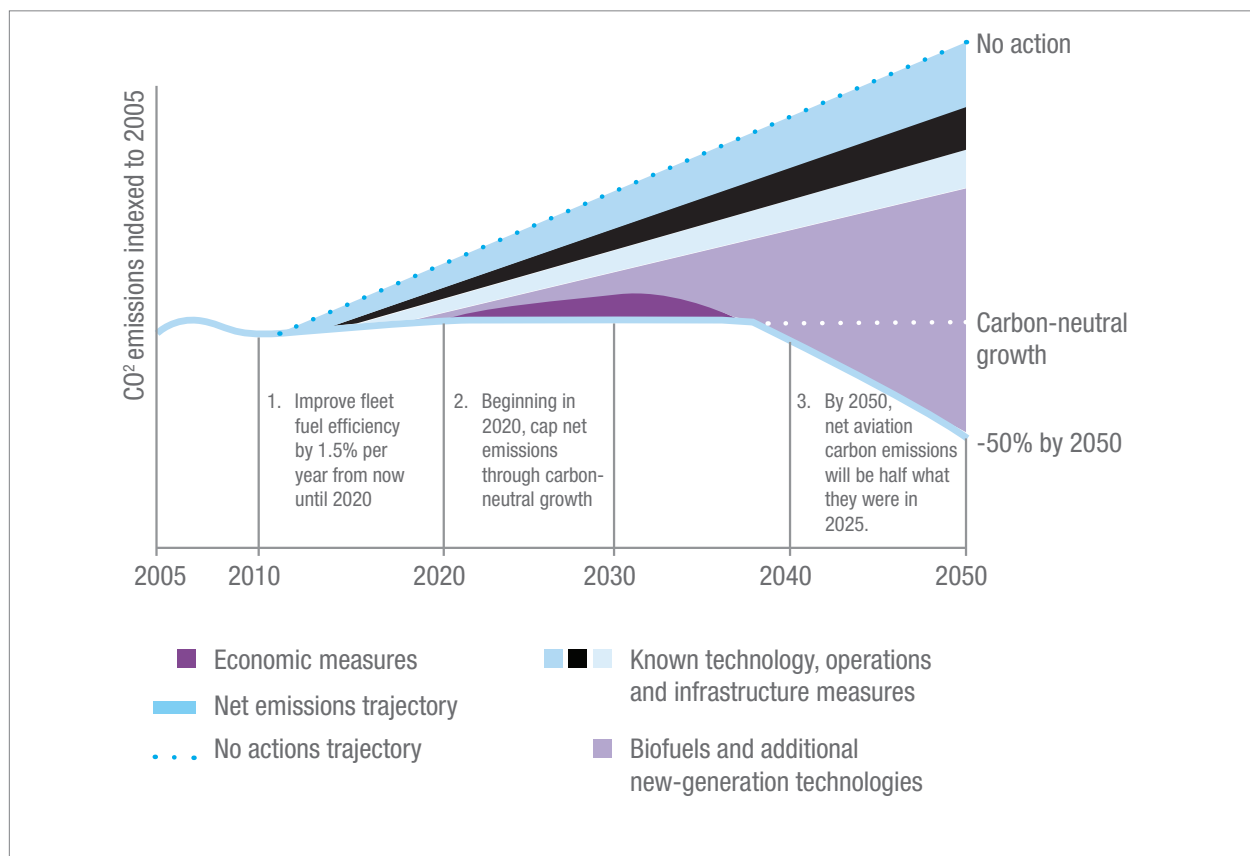


Figure 3. Aeronautics Community Vision for Achieving Carbon Neutrality.

Outcome for 2015-2025: New Transport-class Aircraft that Achieve N+1 Levels of Efficiency. In the near term, mature technology will enable new transport-class aircraft to be designed, developed, and produced that achieve N+1 levels of efficiency and environmental performance.

¹¹ <http://aviationbenefits.org/environmental-efficiency/aviation-and-climate-change/our-climate-plan/>, accessed September 25, 2014

Outcome for 2025-2035: Technology and Potentially New Configuration Concepts that Achieve N+2 and N+3 Levels of Efficiency and Environmental Performance. In the mid term, mature technology and potentially new configuration concepts will enable new transport-class aircraft to be designed, developed, and produced that achieve N+2 and N+3 levels of efficiency and environmental performance.

Outcome for >2035: Technology and Configuration Concepts, Including Low-carbon Propulsion, that Stretch Beyond N+3 Levels of Efficiency and Environmental Performance. In the far term, mature technology and new configuration concepts will enable transport-class aircraft to be designed, developed, and produced that stretch beyond N+3 levels of efficiency and environmental performance. In this timeframe, Low-Carbon Propulsion, as defined in Strategic Thrust 4, is expected to be fully ready for integration in transport-class vehicles, making possible new levels of reduced production of CO₂ and harmful emissions.

Vertical Lift

Community goals for vertical lift aircraft reflect a need for improved performance on a wide variety of missions while enhancing safety and overcoming the historic barriers of speed, efficiency, operating cost, and environmental considerations – particularly noise. Improvements in operational suitability of rotorcraft will enable growth in existing applications, as well as new markets. Further into the future, innovative direct lift and other configurations will further expand the markets for vertical lift, as well as the consequent economic and public good benefits of point-to-point origin-to-destination air transportation. Many UAS applications expected to flourish in the coming decades will call for vertical lift, as illustrated by proposed concepts for retail delivery, search and rescue, exploration, and other missions.

Realizing the potential of these markets will call for meeting aggressive goals in efficiency, noise reduction, and expansion of the speed envelope of vertical lift aircraft. In the near term, technology will continue to improve the safety, noise level, and other attributes of rotorcraft. Mid-term and far-term performance is shown in Table 5 (appearing on page 44), which presents ARMD's preliminary performance targets for noise and fuel efficiency for the N+2 and N+3 vertical lift vehicles that could be introduced between 2025 and 2035.

Outcome for 2025-2035: Technology and Potentially New Configuration Concepts that Achieve N+2 and N+3 Levels of Efficiency and Environmental Performance. In the mid term, mature technology and advances in technology and design approaches will enable new configuration concepts to be designed, developed, and produced that achieve N+2 and N+3 levels of efficiency and environmental performance.

Outcome for >2035: Technology and Configuration Concepts, Including Low-carbon Propulsion and Autonomy, that Stretch Beyond N+3 Levels of Efficiency and Environmental Performance. In the far term, mature technology and advances in technology and design approaches will enable advanced concepts to be designed, developed, and produced that stretch beyond N+3 levels of efficiency and environmental performance. In this timeframe, the convergence of vertical lift, low-carbon propulsion, and autonomy are expected to result in advances in configurations and capability that will open up new markets and missions.

ARMD research supporting Strategic Thrust 3 encompasses two separate families: subsonic transports and civil aircraft that incorporate vertical lift capability.

ARMD's Role

Subsonic Transport

ARMD air vehicle research is segmented into technologies for near-term (2015-2025), mid-term (2025- 2035) and far-term (>2035) generations of vehicles with increasing efficiency and environmental performance. Notional aircraft configurations and enabling technologies, defined by ARMD in collaboration with industry and academia, allow ARMD and the aviation community to estimate integrated aircraft performance that could meet the community's performance goals during these timeframes — 2015 to 2025, 2025 to 2035, and beyond 2035 — with technologies that could be available during those periods.

The notional vehicle concepts are designated as progressively more capable N+1, N+2, and N+3 designs. ARMD's approach is to help enable the rapid evolution of current and emerging revolutionary technologies in the near term while pioneering future technologies and vehicle concepts that will enable transformational improvements in efficiency, noise, and emissions. Throughout, ARMD will continue to support fundamental improvements in vehicle modeling, design, test, and evaluation, as well as advances in aerodynamics and aeromechanics, combustion, and certification and use of composites and other advanced materials.

Together with the aviation community, ARMD will explore advanced vehicle concepts and enabling technologies capable of achieving these improvements. Conceptual designs responding to the N+1, N+2, N+3, and N+4 (beyond 2035) levels of performance serve as “technology collectors,” enabling assessments of the technologies in terms of their impact on attributes of a vehicle design under various scenarios and constraints, as well as their dependencies on other technologies. The conceptual designs also enable comparisons of performance, technical risk, and other attributes of advanced vehicle concepts. In addition, the research will ensure that the safety implications of advanced technologies and concepts are identified and considered in the development process.

The concepts, technologies, and methods with the highest potential impact are prioritized for further R&D. In addition, ARMD conducts crosscutting research, such as advanced computational methods and innovative structural materials, that supports the broad range of vehicle concepts. The result is a base of enabling research and technology for the next generations of vehicles that will be developed and produced by industry. ARMD also partners with industry and the FAA for research in specific areas for early transition to the immediate next-generation (N+1) levels of performance. In addition, ARMD is exploring N+4 concepts and technologies that extend beyond N+3 levels of performance.

Table 3, below, presents the targeted metrics for the N+2 and N+3 subsonic transport vehicles relative to current performance. The table shows target dates for demonstrating the technologies (TRL 4-6) and for first application in a commercial aircraft.

Table 3. Targeted Improvements in Subsonic Transport System-level Metrics

Subsonic Transport Targeted Performance			
Technology Benefits*	Technology Generations		
	N+1 TRL 4-6: 2015 First Application 2020-2025	N+2 TRL 4-6: 2020 First Application 2025-2030	N+3 TRL 4-6: 2025 First Application 2030-2035
Noise (Cumulative margin relative to ICAO 8.4.2/ FAA Stage 4 noise limit)	-32 dB	-42 dB	-52 dB
Landing/Takeoff Cycle NO _x Emissions (Relative to ICAO CAEP/6 standard)	-60%	-75%	-80%
Cruise NO _x Emissions (Relative to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (Relative to 2005 best in class)	-33%	-50%	-60%

Research Themes

The Research Themes described in Table 4, below, support the Outcomes associated with Strategic Thrust 3 for subsonic transport aircraft.

Table 4. Outcomes and Research Themes for Strategic Thrust 3 – Subsonic Transport

Strategic Thrust 3: Ultra-Efficient Commercial Vehicles – Subsonic Transport			
	2015	2025	2035
Outcomes	New Transport-class Aircraft that Achieve N+1 Levels of Efficiency	Technology and Potentially New Configuration Concepts that Achieve N+2 and N+3 Levels of Efficiency and Environmental Performance	Technology and Configuration Concepts, Including Low-carbon Propulsion, that Stretch Beyond N+3 Levels of Efficiency and Environmental Performance
Research Themes	<p>Advanced Ultra-efficient Airframes Research and development of tools and technologies to enable new airframe configurations with high levels of aerodynamic performance, lower structural weight, and innovative approaches to noise reduction</p> <p>Advanced Ultra-efficient Propulsion Research and development of tools and technologies to reduce turbofan-thrust-specific fuel consumption, propulsion noise, and emissions</p> <p>Advanced Airframe-engine Integration Research and development of innovative approaches and the supporting tools and technologies to reduce perceived noise and aircraft fuel burn through integrated airframe-engine concepts</p>		

Vertical Lift

ARMD research for vertical lift (including rotary wing) vehicles aims at aggressive mid-term (2025-2035) goals for efficiency, noise, and emissions to expand current markets and develop new markets. The unique performance characteristics, technologies, and operational environments of rotary wing and other vertical lift vehicles dictate a set of challenges and research themes that differ from those of fixed-wing aircraft. Planned research emphasizes efficient low-noise rotor designs responsive to safety and noise certification standards, as well as efficient variable-speed propulsion systems. ARMD is also studying the possibilities of N+3 vertical lift vehicles with expanded capabilities and N+4 vehicles beyond 2035.

Table 5, below, presents the targeted metrics for the N+2 and N+3 vertical lift vehicles relative to current performance.

Table 5. Targeted Improvements in Vertical Lift Vehicle System-level Metrics

Vertical Lift Targeted Performance (Preliminary)		
Technology Benefits	Technology Generations	
	N+2 TRL 4-6: 2020 First Application 2025-2030	N+3 TRL 4-6: 2025 First Application 2030-2035
Noise (Relative to ICAO 8.4.2/ FAA Stage 3 noise limit)	-10 dB Effective Perceived Noise Level (EPNL)	-14 dB Effective Perceived Noise Level (EPNL)
Fuel/Energy Consumption (Relative to 2005 best in class)	-50%	-60%

Research Themes

The Research Themes described below support the Outcomes associated with Strategic Thrust 3 for vertical lift vehicles.

Table 6. Outcomes and Research Themes for Strategic Thrust 3 – Vertical Lift

Strategic Thrust 3: Ultra-Efficient Commercial Vehicles – Vertical Lift			
2015		2025	2035
Outcomes		Technology and Potentially New Configuration Concepts that Achieve N+2 and N+3 Levels of Efficiency and Environmental Performance	Technology and Configuration Concepts, Including Low-carbon Propulsion and Autonomy, that Stretch Beyond N+3 Levels of Efficiency and Environmental Performance
Research Themes	<p>Clean and Efficient Rotorcraft Propulsion Demonstration and maturation of propulsion and drive system technologies to enable increased vehicle speeds while maximizing propulsive efficiency and minimizing weight penalties</p> <p>Safe and Certifiable Vertical Takeoff and Landing (VTOL) Technologies Technologies to extend the flight envelope and maximize performance and efficiency of VTOL aircraft</p> <p>Advanced Component Noise Reduction Improvements in lift generation, airframe, and other subsystem components to achieve noise reduction</p>		

Major Outcome Risks Addressed by Planned Research

Planned ARMD research for both subsonic transport and vertical lift vehicles addresses the same two risks to achieving the desired Outcomes for Strategic Thrust 3:

- Evolutionary technology improvements alone will be inadequate to meet energy efficiency and environmental constraints while serving future demand for aviation services.
- Without flight demonstration of advanced concepts and technologies, industry will not take the high risk of commercial development, and full energy efficiency and noise performance goals will not be met. This concern is particularly true for advanced alternative vehicle configurations needed to meet the mid- and far-term goals.



This concept for a possible future aircraft is called a “hybrid wing body” or sometimes a blended wing body. This particular version uses a novel “turbo-electric distributed propulsion” concept in which power is electrically distributed from wing-tip gas generators to a series of embedded fans to substantially increase propulsive efficiency and lead to dramatic reductions in fuel consumption, noise, and emissions.



Strategic Thrust 4: Transition to Low-Carbon Propulsion

This section describes Strategic Thrust 4, as well as the community's vision based on priorities identified during dialogue and through strategic analysis that led to development of the Thrust, the Outcomes as capabilities that the aviation community can expect from implementing the results of ARMD research, ARMD's role in implementing the research, and the Research Themes developed by ARMD to support the Outcomes and guide the research conducted within the Strategic Thrust.

Community's Vision

This Strategic Thrust will help to achieve environmental sustainability by enabling absolute reductions in carbon emissions. The air traffic efficiency sought under Strategic Thrust 1 and the vehicle efficiencies sought under Strategic Thrust 3 will greatly reduce the impact of aviation on climate change. However, those efforts alone will not achieve the community's goal of enabling aviation growth with carbon neutrality by reducing net emissions 50% by 2050 compared to 2005 levels. As shown in a position paper prepared by the global aviation industry and illustrated in Figure 3, the community expects this goal to be achieved through a combination of more efficient operations, improved vehicle fuel efficiency and, in the longer term, new propulsion concepts and biofuels.

Strategic Thrust 4 will, therefore, complement the research on improved air vehicles and efficiency of airspace use by focusing on two transformational capabilities: first, the use of low life-cycle carbon fuels for conventional gas turbine engines and their future derivatives, and second, new propulsion systems that use alternative jet fuels and, possibly, renewable energy sources.

The aviation community has high confidence that low-life-cycle carbon fuels for conventional engines can be successfully implemented for use by commercial aviation, and that these will provide significant environmental benefit. There is less certainty that alternative propulsion systems (such as hybrid-electric systems) using other than petroleum-based energy sources can be successfully developed. However, advances in renewable energy and energy systems outside of the aviation sector provide sufficient optimism to pursue these concepts. Successful introduction of non-petroleum-based concepts would provide radically increased environmental benefits.

Hybrid-electric propulsion concepts, employing a combination of conventional and electric power, represent one promising candidate approach for low-carbon propulsion in 2025 and beyond. These concepts employ the best power source or combination of sources to provide the power needed in various flight conditions, and they offer flexible options for airframe designers to reduce drag or achieve

other desired attributes. ARMD has conducted system studies and drafted research plans for this promising approach, and more work is ongoing to understand the full range of options, their benefits, and the hurdles to implementation.

The initial target will be to implement the high-confidence and significant-payoff option of reduced-emission drop-in alternative fuels for conventional engines, since this approach provides the fastest and lowest-risk path to improvements. As that incremental option reaches its maximum potential, fulfilling the community targets for carbon neutrality will require more attention to higher-payoff alternatives by exploring the full range of fuel and propulsion options.

Outcome for 2015-2025: Introduction of Low-carbon Fuels for Conventional Engines and Exploration of Alternative Propulsion Systems. Over the next decade, a suite of lower life-cycle carbon jet fuels will become available for conventionally powered aircraft. At the same time, research will continue in applications of hybrid and fully electric propulsion systems in the general aviation sector for on-demand mobility applications.

Outcome for 2025-2035: Initial Introduction of Alternative Propulsion Systems. In this decade, technology advances required to scale alternative propulsion systems and aircraft configurations will enable possible initial deployment of these technologies on regional jet or single-aisle transport aircraft.

Outcome for >2035: Introduction of Alternative Propulsion Systems to Aircraft of All Sizes. Beyond 2035, alternative propulsion systems and energy sources will be available for operational use on aircraft of all sizes as appropriate to meet operational and economic criteria.

ARMD's Role

ARMD will help to achieve low-carbon propulsion through research in two areas. First, in partnership with the aviation community, is the development of data and analyses to support the use of a suite of certified, commercially available alternative drop-in jet fuels that will lower the total carbon footprint of traditional gas turbine engines and their future derivatives. Second is to explore the possibility of achieving very low or zero carbon emissions through new propulsion systems that leverage the properties of alternative drop-in and non-drop-in jet fuels and renewable energy sources.

In the near term (2015-2025), ARMD will continue working with current collaborators and partners to complete ongoing efforts to lower the emissions of aircraft that use conventional propulsion systems. This effort will include characterization of emissions of alternative jet fuels. In addition, ARMD will engage with the community to explore reduced-scale technology development, initial applications of alternative propulsion systems, and future options for low-carbon propulsion. For the mid term (2025-2035), ARMD will take the lead in identifying, evaluating, and down-selecting alternative propulsion systems. Hybrid-electric propulsion represents one promising candidate approach that ARMD has studied, but more

work is needed to assess the full range of options, their benefits and risks, and hurdles to implementation. Throughout the process ARMD will conduct comparative analyses and selective testing of potential technology advances offering transformative propulsion architectures that might further reduce adverse environmental impacts of aviation.

In the far term (>2035), ARMD will participate in testing and demonstration of full-scale propulsion systems and fuels deemed most effective in the mid-term analyses. ARMD will then support the implementation of alternative systems and fuels for use by the full range of aircraft, including large transport-category aircraft, since this is where the most energy is used and, therefore, where the largest impact on performance lies.

Research Themes

The Research Themes described in Table 7, below, support the Outcomes associated with Strategic Thrust 4.

Table 7. Outcomes and Research Themes for Strategic Thrust 4

Strategic Thrust 4: Transition to Low-Carbon Propulsion			
	2015	2025	2035
Outcomes	Introduction of Low-carbon Fuels for Conventional Engines and Exploration of Alternative Propulsion Systems	Initial Introduction of Alternative Propulsion Systems	Introduction of Alternative Propulsion Systems to Aircraft of All Sizes
Research Themes	<p>Characterization and Integration of Alternative Fuels Characterization of alternative fuels, combustor concepts, and their integration requirements</p> <p>Scalable Alternative Propulsion Systems Technical study of alternative propulsion system architectures and research on key physical attributes and technology enablers to demonstrate fundamental feasibility</p>		

Major Outcome Risks Addressed by Planned Research

- Significant research outside ARMD in critical areas such as batteries and electric motors affords sources for leverage, but targeted research is needed to account for significant differences in requirements for aircraft applications.
- Without ground and flight tests, adoption of new propulsion concepts is very high risk, which would slow the transition of aviation to a low-carbon future.



The Future ATM (Air Traffic Management) Concepts Evaluation Tool, or FACET, is a computer program that generates simulations for managing air traffic scenarios and modeling current or entirely new traffic patterns to see where improvements could be made.



Strategic Thrust 5: Real Time System-Wide Safety Assurance

This section describes Strategic Thrust 5, as well as the community's vision based on priorities identified during dialogue and through strategic analysis that led to development of the Thrust, the Outcomes as capabilities that the aviation community can expect from implementing the results of ARMD research, ARMD's role in implementing the research, and the Research Themes developed by ARMD to support the Outcomes and guide the research conducted within the Strategic Thrust.

Community's Vision

Decades of continuous efforts to reduce risk in commercial aviation have made it the safest mode of transportation. Addressing known hazards and responding to issues illuminated by analysis of incidents and accidents, commercial aviation has achieved exemplary safety records and inspired the confidence of the flying public. As aviation adopts new technologies to enhance the capacity, efficiency, and uses of the NAS, maintaining a safe system will require recognition and timely mitigation of safety issues as they emerge and before they become hazards. A shift toward proactive risk mitigation will become critical to meet these needs.

This Strategic Thrust will deliver a progression of capabilities to ensure safe operations in more complex airspace by accelerating the proactive detection, prognosis, and resolution of emergent threats to system-wide safety.

Outcome for 2015-2025: Introduction of Advanced Safety Assurance Tools. Over the next decade (2015-2025), safety tools such as data mining and analysis, prognostics, real-time system assurance techniques, and safety risk modeling will improve the ability to gain insights and develop solutions. Taking advantage of the increasing availability of aviation system data, identification of safety issues will focus on scaling currently available data mining technologies to process system-wide data. Increased speed and accuracy of analysis tools will support progress toward real-time identification of precursors to emerging safety issues.

Outcome for 2025-2035: An Integrated Safety Assurance System Enabling Continuous System-wide Safety Monitoring. In the subsequent decade (2025-2035), integration of analysis into a live virtual simulation of the NAS will provide a comprehensive picture of system health and facilitate coordination of mitigation strategies. This capability will improve safety assurance through earlier detection of trends and risks system wide. More highly automated safety assessments will enable continuous safety assurance,

and an automated system will evolve over the decade to enable near-real-time assessments as confidence increases in regularly validated system judgments.

Outcome (>2035): Automated Safety Assurance Integrated with Real-time Operations Enabling a Self-protecting Aviation System. Beyond 2035, the automated safety assurance system will become integrated with real-time operations to create an aviation system that exhibits self-protection and self-healing. In the far term, human operators and autonomous systems will collaborate to ensure an optimal mix of corrective actions — from immediate operational adjustments to longer-term system and infrastructure changes — in order to minimize safety risks.

ARMD's Role

Strategic Thrust 5 focuses on research that incorporates novel sensor and networking technologies, along with innovative data analytics, to enable unprecedented insight into system operations, health, and safety. System-of-systems modeling, prognostic tools, and run-time system assurance technologies will enable real-time, system-wide safety assurance at all levels, from individual component elements to a system of systems.

The ultimate Outcome of this Strategic Thrust is to promote proactive safety management through the development of a prototype for real-time system-wide safety assurance. The building blocks of such a system are data analysis, prediction, and assessment tools that enable continuous monitoring to detect and mitigate potential safety threats at all levels of the aviation system including producers, suppliers, and others involved in assuring aviation safety.

The Outcomes represent sequential scaling, acceleration, and eventual automation of methods to detect, predict, and mitigate safety threats. Current anomaly detection and prediction techniques will be scaled to incorporate heterogeneous data from individual systems in the near term (2015-2025) and systems of systems in the mid term (2025-2035) to achieve an eventual goal of monitoring across the system-wide elements of the NAS in the far term (>2035). ARMD's activities will support increasing levels of automation through scaling of system assurance tools and integration of component-level detection, prediction, and mitigation strategies. Research efforts will leverage ongoing advances in sensing, computation, communications, prognostics, and data analytics to enhance access to and maintain protection of sensitive data. These efforts will enable increasingly rapid discovery, alerting, and mitigation of anomalous events. Research will culminate in an integrated demonstration of a prototype real-time system-wide safety assurance system.

Research Themes

The Research Themes described in Table 8, below, support the Outcomes associated with Strategic Thrust 5.

Table 8. Outcomes and Research Themes for Strategic Thrust 5

Strategic Thrust 5: Real-Time System-Wide Safety Assurance			
	2015	2025	2035
Outcomes	Introduction of Advanced Safety Assurance Tools	An Integrated Safety Assurance System Enabling Continuous System-wide Safety Monitoring	Automated Safety Assurance Integrated with Real-time Operations Enabling a Self-protecting Aviation System
Research Themes	<p>System-wide Data Analysis for Understanding Safety Events Technical approaches for integrating sensitive data from heterogeneous sources to build base models of nominal and off-nominal system performance and improve accuracy of detection and prediction tools</p> <p>Improved Performance of Detection, Analysis, and Prognostic Tools Increased speed and scaling of tools to enable rapid detection of safety threats in large, heterogeneous data sets as they arise</p> <p>Integrated Threat Prognosis, Alerting, and Guidance Architecture for integration of scaled, automated methods for threat alerting, prognosis and guidance to improve mitigation strategies; simulation tools for real-time operational evaluation</p> <p>Techniques for Real-time Safety Assurance Advances in verification techniques to be applied during operation of systems to monitor performance, efficiently analyze risks, and rapidly provide potential solutions</p> <p>Real-time System-wide Safety Assurance Demonstration Integrated demonstration of a real-time system-wide safety assurance prototype system</p>		

Major Outcome Risks Addressed by Planned Research

- Access to sensitive data from all elements of the system is essential for both the development of validated tools and effective real-time monitoring.
- Processes and tools for data protection, as well nontechnical aspects of building trust within the community, will be critical.



Silhouetted by the morning sun, NASA's Ikhana, a civil version of the Predator B unmanned aircraft, is readied for flight at NASA's Armstrong Flight Research Center. The Ikhana has been used to perform research supporting integration of unmanned aerial systems into the National Airspace System.



Strategic Thrust 6: Assured Autonomy for Aviation Transformation

This section describes Strategic Thrust 6, as well as the community's vision based on priorities identified during dialogue and through strategic analysis that led to development of the Thrust, the Outcomes as capabilities that the aviation community can expect from implementing the results of ARMD research, ARMD's role in implementing the research, and the Research Themes developed by ARMD to support the Outcomes and guide the research conducted within the Strategic Thrust.

Community's Vision

The evolution of autonomous systems will transform aviation operations, providing improvements in safety, efficiency, and flexibility of operations to increase the capacity, robustness, and flexibility of the NAS. Additional benefits will be realized through new uses of the airspace, enabled by advances in autonomy such as advanced UAS operations and on-demand personal air transportation. The objective of Strategic Thrust 6 is to enable autonomous systems that employ highly intelligent machines to maximize the benefits of aviation to society.

Outcome (2015-2025): Initial Autonomy Applications. The near-term decade will see initial integration of UAS capabilities into the NAS, as well as exploitation of autonomous systems technologies within the aviation infrastructure. Operation of small, highly automated or autonomous vehicles within specially designated areas, as well as integration with more conventional aviation operations where appropriate, will address a community need and provide a testbed for further development of highly automated aviation operations. Other early applications of autonomy, such as autonomous emergency landing systems, will improve system performance and safety.

Outcome (2025-2035): Human-machine Teaming in Key Applications. For the mid term, advances from the previous decade will support development of more sophisticated human-machine teaming concepts, such as reduced crew commercial operations. Increasing trust in autonomous systems will open a pathway to restricted certification of fully autonomous UAS for selected applications. This timeframe will see a combination of increasing efficiency of the air transportation system within the mid-term operational paradigm and growing application of autonomous systems. The prospective introduction of trajectory-based operations (TBO) will provide another opportunity for large gains from autonomous system technologies.

Outcome (>2035): Ability to Fully Certify and Trust Autonomous Systems for NAS Operations. In the far term, aviation will make widespread use of autonomy across a broad range of NAS functions. Techniques for verification, validation, and systems certification of complex, joint human-machine cognitive systems will establish trust in autonomous systems and allow for eventual certification of the full range of autonomous operations.

ARMD's Role

The focus of Strategic Thrust 6 is to apply innovative technologies to the problem of enabling autonomous aviation operations. ARMD will leverage rapidly evolving developments in machine learning, robotics, and adaptive, cognitive computing architectures to enable high-impact autonomy applications. These efforts will be complemented by extensive research and development of methods and capabilities to validate and assure trusted performance of highly complex systems-of-systems with substantial adaptive characteristics. Special focus will be placed on assessing the ability of machine learning functions to adapt to emergent conditions. The research will employ sophisticated testbeds to understand key challenges and develop solutions for specific applications.

ARMD's primary role will be in development of concepts, architectures, and applications for autonomous aviation systems. In the near term (2015-2025), ARMD research will focus on integrating UAS capabilities in the NAS. Research for this timeframe will also help to define the benefits and risks of potential autonomous systems, facilitating selection of the most appropriate candidates for focused research and application. Evolution of the test infrastructure will support critical exploration and validation activities. In the mid term (2025-2035), exploration of new technologies and applications will lead to advances in human-machine teaming, enabling new concepts of operation that promote greater system efficiency. Research for the far term (>2035) will help to enable the application of autonomous functions across the NAS by developing standards and techniques for assured performance in high-complexity environments.

Research Themes

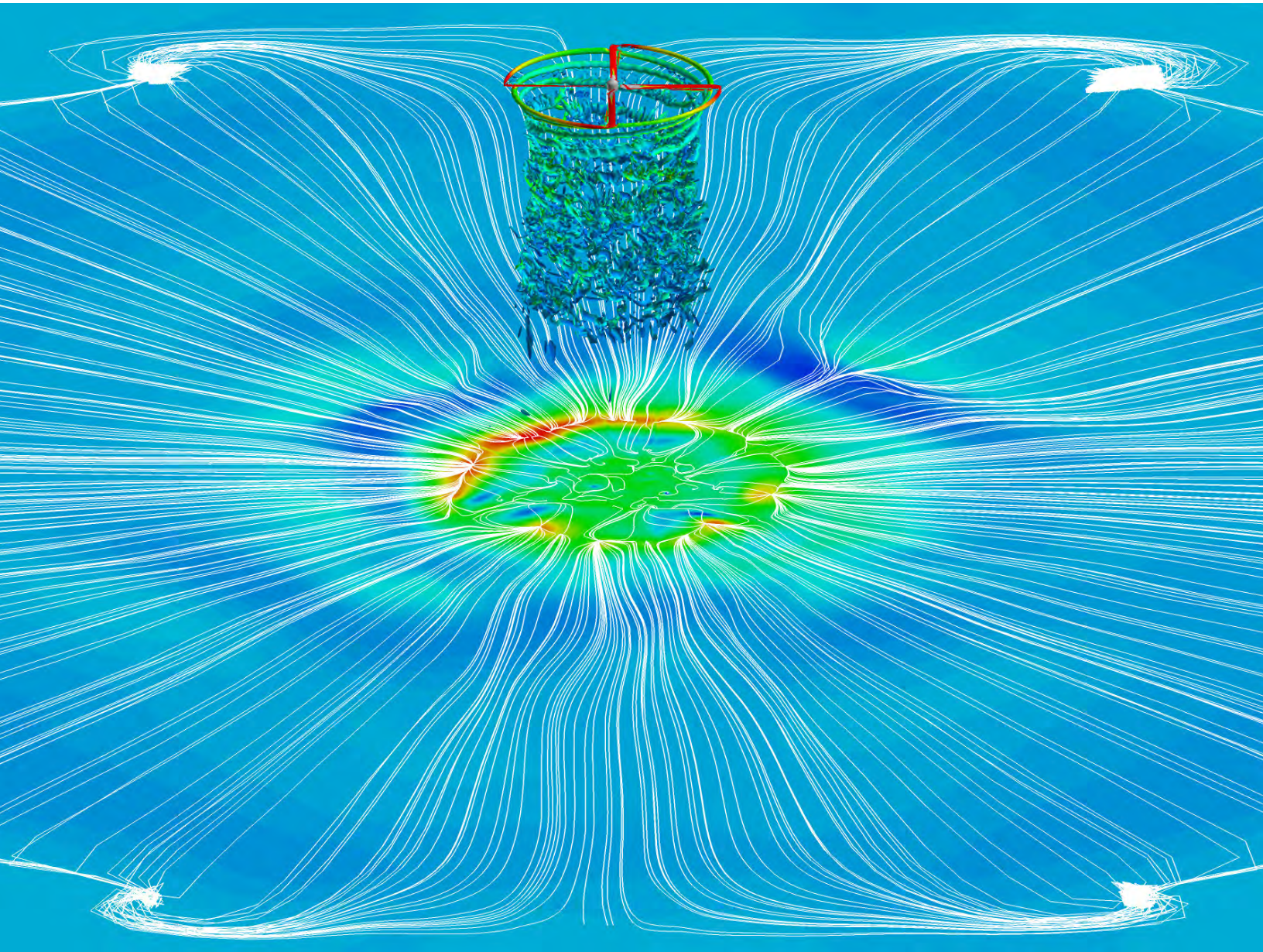
The Research Themes described in Table 9, on page 57, support the Outcomes associated with Strategic Thrust 6.

Table 9. Outcomes and Research Themes for Strategic Thrust 6

Strategic Thrust 6: Assured Autonomy for Aviation Transformation			
	2015	2025	2035
Outcomes	Initial Autonomy Applications	Human-machine Teaming in Key Applications	Ability to Fully Certify and Trust Autonomous Systems for NAS Operations
Research Themes	<p>UAS Integration Airspace integration procedures and performance standards to enable UAS integration in the air transportation system</p> <p>Validation, Verification, Testing, and Evaluation Application of assurance technologies to validate performance of autonomous systems in a variety of known (i.e., conceivable) operational scenarios; extension of traditional verification and validation techniques to ensure trust and confidence in the performance of machine learning, and sense-making autonomy functions capable of adapting to conditions of the unknown unknown type</p> <p>Design and Analysis of Autonomous Systems Development of core automation for supporting specific autonomy operational needs in functional areas such as navigation, communication, surveillance, and robotics, and design of architectures for integration of technologies into an autonomous system</p> <p>Autonomous Planning, Scheduling, and Decision Making Development and application of advanced cognitive computing architectures and sensory technologies for reasoning and decision making, and capabilities for engaging unknown unknowns in the operational environment as part of human-machine cognitive systems</p> <p>Vehicle Control, Health Management, Adaptation, and Multivehicle Cooperation and Interoperability Application of autonomy to assist human-in-vehicle operations and expanding vehicle health management capabilities</p>		

Major Outcome Risks Addressed by Planned Research

- Strategic partnerships will be critical to maintaining awareness of unknown issues and risks, as well as providing opportunities to explore unique solutions.
- Verification and validation challenges must be addressed as a key factor affecting the pace of progress.
- Nontechnical issues, such as legal liability, public acceptance, moral decision making, and transformation of human roles and tasks, could pose barriers to applications of UAS and other uses of machine intelligence.



To help develop more efficient rotorcraft designs, engineers need to better understand the complex airflow interactions caused by the spinning rotor. CFD simulations of experimental rotor hover tests help researchers improve and validate the accuracy of the computational models and help engineers design better wind tunnel experiments.

Crosscutting Research & Testing

In addition to research that directly aligns with specific Strategic Thrusts, ARMD conducts foundational research on crosscutting ideas and technologies that provides critical support to other aeronautics and aerospace applications and explores opportunities for technology convergence. Flight and ground capabilities for experimentation and feasibility demonstrations are additional elements that support the research for multiple Strategic Thrusts.

Crosscutting research falls mainly into two areas: (1) next-generation physics-based modeling and design capabilities to enable realization of long-term vehicle and aviation system design concepts, and (2) enabling transformation of flight capabilities through innovations in discipline-oriented technologies such as new materials, measurement techniques, and flight and propulsion controls.

Research in revolutionary tools seeks to develop a multidisciplinary computational capability for modeling a broad range of phenomena of interest to aeronautics, including turbulent flow, transition, supersonic flow, reacting flow, acoustics, and other aspects of fluid physics, as well as development and validation of autonomous vehicle system control concepts enabling rapid progress from concept to flight. This research includes a range of capabilities, from system-level air vehicle design, analysis, and optimization tools, to high-fidelity computational fluid dynamics and structural and aeroelastic dynamics tools. Innovative numerical algorithms will take advantage of new computer architectures to make computational analysis faster and more efficient. Targeted validation experiments will develop databases for model assessment and validation, as well as providing insight for development of improved modeling ideas.

Transformational advances in discipline-oriented technology areas, such as materials, measurement techniques, and flight and propulsion controls, are required to enable advanced vehicle and propulsion system concepts for the future. These technologies range from new materials that enable improved capability, to novel sensors, to advanced actuators. Innovative measurement techniques, including optical techniques for both surface and off-body measurement, will improve diagnostic capability, as well as provide the advanced measurement capability needed for the validation experiments supporting development of tools and methods.

ARMD's flight and ground test capabilities, complemented by high-fidelity computational simulation, enable rapid experimentation and feasibility demonstration of advanced concepts ranging from individual experiments, to proof-of-concept tests, to demonstration of integrated concepts embodying converging technologies. Relevant assets include flight research and support aircraft; wind tunnels; propulsion, acoustic, materials, and structures laboratories and test facilities; flight research and aircraft traffic management simulators; airspace operations laboratories; high-end computing laboratories; and test support infrastructure. These facilities and capabilities will continue to evolve in support of the research necessary to address the Strategic Thrusts.



Every U.S. aircraft and U.S. air traffic control tower has NASA-developed technology on board, working to improve performance and efficiency.

Conclusion

The coming decades represent both a great opportunity for aviation to serve a growing demand driven by global socioeconomic development and a major challenge to do so with minimum adverse impact on the environment. NASA's aeronautical research, carried out by ARMD, will play a leading part in enabling an efficient, flexible, scalable, and environmentally sustainable aviation system that will meet global needs for air transportation through 2035 and beyond. These needs are shaped by three Mega-Drivers: global growth in demand for high-speed mobility; global climate change, sustainability, and energy use; and technology convergence.

While carrying out its traditional role of conducting research outside the economic and risk criteria that govern commercial investments, ARMD will continue to develop and apply new technologies and promote innovation to support six Strategic Thrusts:

- Safe, Efficient Growth in Global Operations
- Innovation in Commercial Supersonic Aircraft
- Ultra-Efficient Commercial Vehicles
- Transition to Low-Carbon Propulsion
- Real-Time System-Wide Safety Assurance
- Assured Autonomy for Aviation Transformation

ARMD's strategic planning emphasizes enabling the achievement of Outcomes expressed as societal or economic benefits within these Strategic Thrusts. Viewing the NAS as a complex system of systems and working closely with the aviation community, ARMD research will leverage new or nontraditional technologies and approaches, including alternative fuels and electric or hybrid propulsion, low-sonic-boom supersonic flight, automation and autonomy, and technology convergence to develop transformative solutions. The ultimate goal is to enable a safe, efficient, adaptive, scalable, and environmentally sustainable global aviation system to meet the challenges of the future.

Join the Conversation

This Strategic Implementation Plan is a living document through which NASA communicates with stakeholders and the research community. Feedback is welcome and encouraged and can be sent to Brenda Mulac at brenda.l.mulac@nasa.gov.

Acronyms List

3-D	Three-dimensional
AAVP	Advanced Air Vehicles Program
AOSP	Airspace Operations and Safety Program
ARMD	Aeronautics Research Mission Directorate
ATAG	Air Transport Action Group
ATM	Air Traffic Management
BWB	Blended Wing Body
CAEP	Committee on Aviation Environmental Protection
CAST	Commercial Aviation Safety Team
CFD	Computational Fluid Dynamics
CLEEN	Continuous Lower Energy, Emissions, and Noise (Program)
CNG2020	Carbon Neutral Growth 2020
CO ₂	Carbon Dioxide
dB	Decibel
DoD	Department of Defense
EM	Emerging Market
EPNL	Effective Perceived Noise Level
EU	European Union
FAA	Federal Aviation Administration
IASP	Integrated Aviation Systems Program
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
NACA	National Advisory Committee for Aeronautics
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NASTRAN	NASA Structural Analysis
NextGen	Next Generation Air Transportation System
NO _x	Nitrogen Oxides
R&D	Research and Development
SESAR	Single European Sky Air Traffic Management Research
TACP	Transformative Aeronautics Concepts Program
TRL	Technology Readiness Level
U.S.	United States
UAS	Unmanned Aircraft System(s)
VTOL	Vertical Takeoff and Landing

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